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UNDERGROUND COAL GASIFICATION – THE VELENJE COAL MINE ENERGY AND ECONOMIC CALCULATIONS

Article Highlights

- Energy and economic calculations for underground coal gasification were performed
- The location for the pilot experiment in Velenje Coal Mine was reviewed
- A new procedure for the estimation of the energy efficiency was proposed
- The energy analyses for different examples of coal exploitation were compared
- The viability of the underground coal gasification project in Velenje was determined

Abstract

Underground coal gasification (UCG) is a viable possibility for the exploitation of vast coal deposits that are unreachable by conventional mining and can meet the energy, economic and environmental demands of the 21st century. Due to the complexity of the process, and the site-specific coal and seam properties, it is important to acknowledge all the available data and past experiences, in order to conduct a successful UCG operation. Slovenia has huge unmined reserves of coal, and therefore offers the possibility of an alternative use of this domestic primary energy source. According to the available underground coal gasification technology, the energy and economic assessment for the exploitation of coal to generate electricity and heat was made. A new procedure for the estimation of the energy efficiency of the coal gasification process, which is also used to compare the energy analyses for different examples of coal exploitation, was proposed, as well as the technological schemes and plant operating mode in Velenje, and the use of produced synthetic coal gas (syngas). The proposed location for the pilot demonstration experiment in Velenje Coal Mine was reviewed and the viability of the underground coal gasification project in Velenje was determined.

Keywords: underground coal gasification, syngas, clean coal technology, energy analysis, economic analysis.

Coal will remain the leading energy resource in the following decades [1,2], which is why the development of technologies, which will enable and maintain the coal's competitiveness against other energy resources, is expected. In recent years, there has been increased interest in clean coal technologies, one of which is the process of underground coal gasification (UCG), which combines the technologies of excavation and transformation of coal into useful energy [3]. UCG is the unconventional utilisation of coal, with the use of injection and production boreholes, which are employed for the conversion of coal to gas [3]. Gases from coal can be directly produced *in situ* by providing the gasification agent (air, oxygen) into the ignited coal seam, and collected on the surface [3,4]. This allows for the extraction of deep and un-minable coal and lignite resources [1,5,6]. The produced syngas can serve as a fuel for energy production or can be further processed in the chemical industry (hydrogen, ammonia, methanol, liquid fuels, *etc.*) [6-9].

The UCG process is one of the most innovative technologies being developed around the world [1,4], and offers the possibility to use the energy from coal

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in an economically viable and environmentally friendly manner, since it causes far less gas emissions and solid particle production after the combustion of coal, as is the case with conventional coal-fired power plants [10,11].

However, the UCG technology is still not commercially feasible in spite of many statements, methodologies, suggestions, monitoring techniques, *etc*. Commerciallization could be reached in the next 5 to 10 years as many field tests are currently running worldwide (South Africa, Australia, India, USA, China, *etc*.) [5,11-12]. Some of the well-documented UCG operations are those at Angren (Uzbekistan), Queensland (Australia), Alberta (Canada), Walanchabi City (China), Majuba (South Aferica) [6]. UCG development is hindered by the infancy of the technology and the limited operational experience on a commercial large scale [13]. Apart from this, UCG has experienced a lot of uncertainty in its development life due to coal shortage/abundance and the fluctuations in the price of other resources such as natural gas and oil [10]. While it can be said that it is possible to gasify all coal types, some specific conditions require a specific UCG method. UCG tests throughout the world have been made at different operating conditions in different coal types, at different depths and in different thicknesses of coal seams. Very few tests were done on lignite and none in thick seams where the underground gasifier control would be difficult [7,14]. Tests show how the variations in geological setting, hydrogeological conditions, coal composition, and UCG process realisation affect process control, dirt transport, economy of the process, environment and people's health [7,14]. Many tests were realised in shallow deposits (less than 100 m deep) [7,11], which is not the target depth for commercial UCG development. The pressures that can develop and the possibility of gas migration (escape) limit these processes in shallow deposits [14].

In Slovenia, UCG studies started at the beginning of the 1980s with laboratory investigations of smaller samples, and continued with test gasification of larger blocks of lignite. Research has been done on Velenje lignite and Zasavje brown coal. A study on the sustainable development of Velenje mining had been performed [15] and in 2002 a feasibility study of UCG was done in the Velenje coalmine. One of the thickest layers of lignite in the world, which is found in the Šaleška Valley, contributed to the development of innovative excavation methods and other technologies like UCG [8]. Because the research was interrupted, some important parts of UCG are still missing: assessment of the use of the process products, along with the economic and final evaluation.

All phases of research performed so far have been performed with the intention to gather evidence about the possibility of performing the UCG process in the coal seam of the Velenje basin. This research represents a demonstration and an important foundation for the implementation of an *in situ* pilot test of UCG in Velenje.

EXPERIMENTAL

The geometry of the test and the operating parameters for the Velenje UCG have been estimated and adjusted on the basis of the modular gasification scheme of the company Carbon Energy Pty Ltd. (CEPL), which was made in the framework of a test in Bloodwood Creek in Australia [16]. The latter offers the most comprehensive data available. Carbon Energy is one of the leading companies in the world in the field of advanced coal technologies such as UCG. Different experiences from previous tests performed around the globe were also taken into account in our procedure.

The energy-economic estimate of the implementation of the pilot testing and modular operation of the plant for the exploitation of syngas is our copyright work, as there are no data available in contemporary literature on the actual implementation of the UCG process for commercial purposes. A new procedure for the estimation of the energy efficiency of the selected UCG method, which is also used to compare the energy analyses for different examples of coal exploitation, is presented, as well as the procedure of economic analysis of the implementation of the pilot UCG test at the Velenje Coal Mine. This part contains the new calculation method for the aforementioned analysis. The following calculations were performed for the estimation of the energy efficiency of the selected UCG method:

- The calculation of the energy efficiency obtained from coal using traditional conventional coal mining. This served as the basis for how much energy might be obtained from an anticipated quantity of coal. The calculation was made on the assumption that coal is excavated and used in a thermal power plant.
- The calculation of the energy efficiency with the use of the UCG method with the assumption of ideal gasification efficiency.
- The calculation of the energy efficiency with the use of the UCG method with the assumption of realistic 80% gasification efficiency. 80% efficiency

means that 80% of the original heating value of the coal feedstock is recovered at the surface in the form of the energy of the produced syngas. The loss of the heating value is simply the consequence of the irreversible heat loss to the surrounding, which becomes larger once more overburned is exposed [17].

- The calculation of the energy efficiency of the UCG method in comparison with a traditional method with a coefficient of energy efficiency of UCG with realistic efficiency and energy efficiency of traditional mining method.

The value of coal per tonne can be calculated from the calorific value (h_{lignite}; GJ/t) and selling value (SV; €/GJ):

$$V = h_{\text{lignite}} \times SV \tag{1}$$

The energy value of 1 module (W_{module}; GJ):

$$W_{\text{module}} = h_{\text{lignite}} \times m_{\text{module}} \tag{2}$$

where m_{module} is the mass of 1 module. The calorific power of 1 module ($P_{\text{coalmodule}}$) can be calculated:

$$P_{\text{coalmodule}} = \frac{W_{\text{module}}}{t} \eta_{\text{gasification}} \tag{3}$$

where t is the time of operation and $\eta_{\text{gasification}}$ is the gasification efficiency.

RESULTS AND DISCUSSION

The research performed so far indicates that, given the properties of the Velenje coal field, the most appropriate UCG technology method combines the ELW method (Extended Linked Wells) and the modified CRIP (Controlled Retraction Injection Point) method for ignition and underground gasification, as shown in Figure 1. This UCG technology is founded on the data of the Australian company Carbon Energy Pty Ltd. (CEPL) [16]. The geometry of the test and operational parameters of UCG in Velenje have been estimated on the basis of the modular gasification scheme of the company CEPL, which was made in the framework of the test in Bloodwood Creek in Australia. The CEPL technology includes two parallel wells drilled from the surface to the block of coal, which come closer together near the vertical ignition well. Then the CRIP method of gasification and controlled retraction of ignition point and reaction cavity is used. Here, the well in the coal seam is linked to the vertical wells, while the gasifier in the injection well retracts towards the entrance.

UCG energy analysis

The energy value of a coal module is calculated for conventional mining, *e.g.*, if the lignite is excavated and used in a thermal power plant. The field of coal of one UCG module in the size of 600 m×180 m×8 m comprises m_{module} = 1,149,120 t ≈ 1.1 Mt of coal. The calorific value of coal or the average energy value of lignite of h_{lignite} = 10 GJ/t and the specific weight or the volumetric mass of coal of ρ_{lignite} = 1.33 t/m^3 were used. The calorific value of lignite is low (10 GJ/t) due to the high moisture content. In contrast, the calorific value for coal is around 25.5 GJ/t, *e.g.*, Polish hard coal [18], or 28.5 GJ/t Mannville sub-bituminous coal [19]. The economic or operational cycle of one module of coal is $t_{\text{UCG}} = t_{\text{UCGmodule}}$ = 2.3 years = 28 months = 20,160 h. The expected energy value of one burnt module of coal is W_{module} = 11,491,200 GJ.

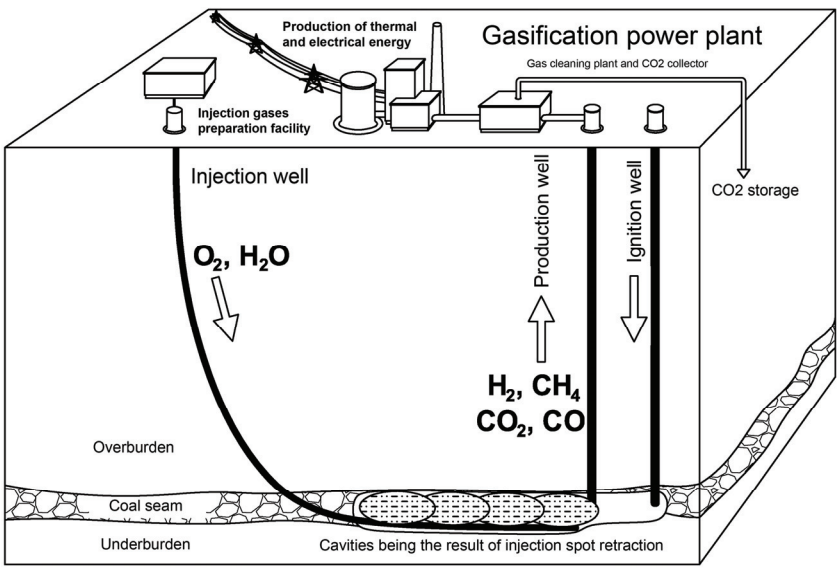

Figure 1. In situ principle of coal gasification according to the CRIP method.

The available calorific power of one module of coal with traditional mining is $P_{coalmodule}$ = 158.33 MW.

The expected available thermal energy (operational energy) of dry gas of one module at thermodynamic equilibrium (T_{UCG} = 880 K, p_{UCG} = 10 bar) with injected oxygen is calculated to be W_{gas} = = 10,714,012 GJ. Thus, the expected thermal power of gas at the surface or the available thermal operational power of the UCG plant, respectively is P_{module} = 147.62 MW. By comparing the available energy of the obtained gas and energy of coal, which is the subject of gasification, we can estimate the efficiency of gasification, which, given these conditions, accounts for $\eta_{UCGprocess}$ = 93.2%. According to these calculations, 93.2% of all available energy in a certain coal seam can be obtained through gas. This confirms our assumptions that the energy value of the gasification products is slightly lower with the UCG method than with traditional mining.

Table 1 comprises a summary of the energy analysis for different examples of coal exploitation.

Below is a detailed presentation of underground coal gasification with the gasification efficiency of 80%. Further on, the energy and economic analysis are presented.

An optimal feed rate of reagents and the obtained syngas depend on the type of coal, thickness of a coal seam and conditions under which the gasification process takes place. This paper contains indicative average values expected for the operational cycle of one module. The flow of gas injected into the module has to be adjusted during the procedure in order to maintain a stable ratio between the oxygen flow and the surface of the combustion cavity formed during the procedure. This maintains the ratio between the extracted and released heat, which in turn ensures constant operating conditions and therefore a constant composition of syngas. The calculations are made on the assumption of equilibrium temperature, which ensures a satisfactory compatibility with experimental measurements. The fact that the coal used during laboratory test was not identical to the coal in the seam (humidity, operating pressure), must be taken into account. It can also be assume that the oxygen to vapour ratio has a lower impact on the economics of UCG itself, as geological properties of coal (such as thickness and gradient of the seam) have a stronger effect.

In Figure 2, the results of the calculations are presented, which were made on the assumption of coal gasification efficiency of $\eta_{gasification}$ = 80% and at a pressure of 10 bar [19]. This means that with the efficiency of 80%, the same amount of energy from the coal will be transferred to the energy of the syngas formed during the gasification procedure. It has to be taken into account that even if the gasification efficiency changes, the calorific values of the syngas remain unchanged, as in the case when different

Table 1. Energy analysis of coal exploitation

Size per one module of coal	Conventional mining	UCG at ideal efficiency	UCG at 80% efficiency of gasification
Energy value	W_{module} = 11,491,200 GJ	W_{gas} = 10,714,012 GJ	$W_{gas80\%}$ = 9,269,846 GJ
Thermal power of a power plant	$P_{coal\ module}$ = 158.33 MW	P_{module} = 147.62 MW	$P_{gas80\%}$ = 127.73 MW

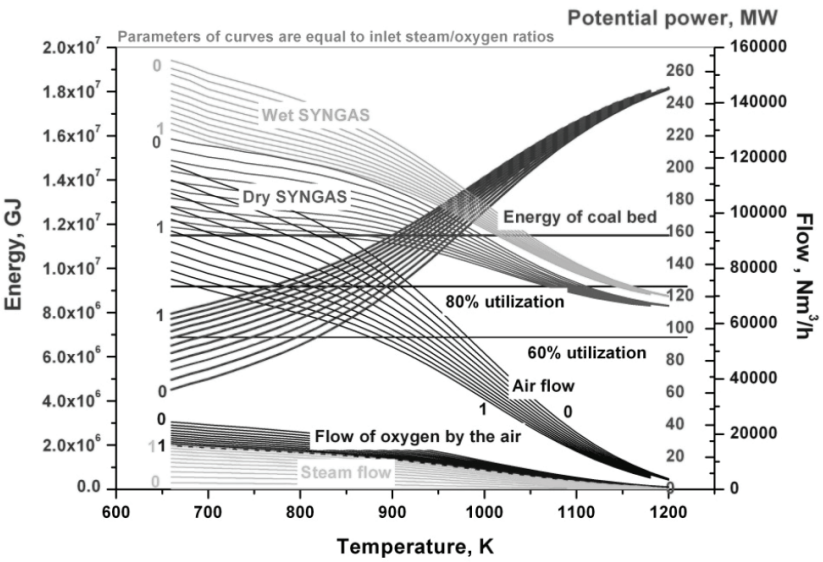

Figure 2. Material flows for the operation of the test module in the stream of both oxygen and steam [19].

flows of reagents and products are used. The water content can also be noticed on the diagrams, which means that both dry and wet coal syngas can be compared. The starting point is an equimolar mixture of steam and oxygen, which means that the molar ratio of both elements is 1:1. The chart also features individual curves of which each indicates a 10% decrease of water intake until the stage of gasification with pure oxygen (no steam is present at this stage) is reached.

According to the results of Velenje lignite laboratory gasification, the most appropriate steam/oxygen ratio is 1:1 [14]. It is generally believed that the best conditions for lignite UCG are obtained, if the Velenje lignite is gasified with the mixture of H_2O and O_2 in a 1:1 ratio, which means that this is the best gasification agent or the best gasification ratio.

The flows of individual gas streams with 80% coal gasification are represented in Figure 2 for both borderline cases: in oxygen or air stream with added steam or without it. With the gasification efficiency of $\eta_{gasification}$ = 80%, the optimal conditions of gasification are established at the temperature of $T_{UCG80\%}$ = 782 K and pressure of $p_{UCG} = p_{UCG80\%}$ = 10 bar. The anticipated available thermal power of the UCG process with the gasification efficiency of 80% is estimated at $P_{UCG80\%}$ = 126 MW.

The aforementioned method was also used in the report "Sizing and economics of power plant based on reserves, products and energy utilization of UCG process", which was prepared by PV (Velenje Coal Mine) as an enclosure to a study of IREET (Energy, Ecology and Technology Research Institute, Ljubljana). In it, costs are specified for the installation, maintenance and operation of a virtual energetic plant that would operate on lignite and use the process scheme proposed by Carbon Energy. A default size of the gasification field was assumed to be 600 m×180 m×8 m and the rate of the progression of the combustion front was set to 3 cm/h.

Figure 2 shows operational parameters for a test gasification of a hypothetical field of lignite with the assumed operational period of 2.3 years in the stream of both oxygen and steam. A constant speed of advancement or progression of combustion and/or gasification front is also taken into account. In reality, only the conditions indicated in the lower left part of the chart are possible, where the "energy" lines lie below the "energy of coal". Optimal gasification is observed with the following parameters: efficiency of 80%, 1:1 steam/oxygen ratio, temperature of $T_{UCG80\%}$ = 782 K, pressure of $p_{UCG80\%}$ = 10 bar and at the thermal power energy line of $P_{UCG80\%}$ = 126 MW.

The gasification efficiency of $\eta_{gasification}$ = 80% is assumed for further calculations, which means that the same amount of energy from coal obtained with a conventional method will be transferred to the energy of syngas formed during the gasification process.

The estimated values of previous chemical tests, the obtained available thermal energy and the required material flows at the default rate of gasification and different efficiencies for one module in the stream of oxygen and steam are represented in Table 2.

Table 2. Material flows for the operation of the test module in the stream of both oxygen and steam [13]; energy of one module of coal: 11,491,200 GJ

Parameter	Value		
Gasification efficiency, %	80	80	60
H_2O:O_2 ratio	1:1	0:1	0:1
Quantity of dry gas obtained, m^3/h	38,744	44,991	39,851
Quantity of oxygen needed, m^3/h	13,538	15,875	19,784
Quantity of steam needed, m^3/h	13,538	-	-
Quantity of water needed, kg/h	10,878	-	-
Available heat, MW	126	126	95

At the gasification efficiency of $\eta_{gasification}$ = 80% the volume of dry syngas at $q_{gas80\%}$ = 38,744 m^3/h or of wet syngas at $q_{gasH2O80\%}$ = 65,595 m^3/h was taken into account, enabling the available thermal power of $P_{UCG80\%}$ = 126 MW. With a 1:1 oxygen/steam ratio, q_{O2} = 13,538 m^3/h of oxygen and the same amount of steam q_{steam} = 13,538 m^3/h or water q_{H_2O} = 10,878 kg/h is needed, which is shown in Figure 3. The flows of gases were defined or calculated for a default speed of advancement of a combustion front, a default composition of lignite and an assumed chemical equilibrium under certain conditions. The entire required quantity of air, oxygen, water and steam for one module are of indicative nature only and are used to estimate how much energy will be possible to obtain by gasification of one coal module.

According to data from Table 2, at the gasification efficiency of 80% the quantity of dry syngas obtained from one module equals to $K_{gasUCG80\%}$ = = 7,810,790,400 m^3.

A calorific value of $q_{gas80\%}$ = 11,868 kJ/m^3 of dry syngas is taken into account at a temperature of $T_{UCG80\%}$ = 782 K, as temperature has an almost insignificant effect on the calorific value of the obtained gas in the temperature range between 700 and 900 K. When the same calorific value of the obtained syngas is used at thermodynamic equilibrium and efficiency of 80%, the thermal energy of gas from one module equals to $W_{gas80\%}$ = 9,269,846 GJ.

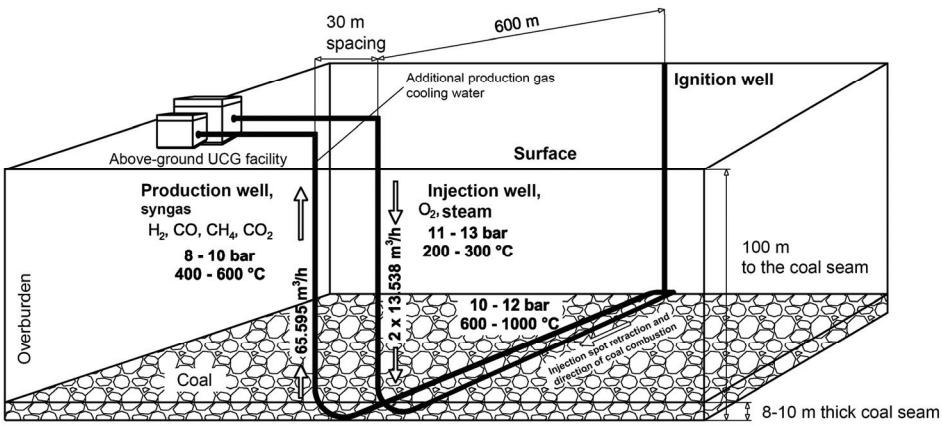

Figure 3. The technological scheme of the UCG process from Bloodwood Creek adapted for a module of coal in Velenje [16].

A summary of the analysis of energy parameters for underground coal gasification at the gasification efficiency of 80% is represented in Table 3.

Table 3. Energy analysis of UCG at the gasification efficiency of 80%

Parameter	Value
Quantity of syngas obtained from one module of coal	$K_{gas80\%}$ = 781,079,040 m^3
Thermal energy for one module	$W_{gas80\%}$ = 9,269,846 GJ
Quantity of syngas obtained from ten modules of coal	$K_{gasUCG80\%}$ = 7,810,790,400 m^3
Energy value of ten UCG modules	$W_{UCG80\%}$ = 92,698,460 GJ
Thermal power of dry gas	$P_{gas80\%}$ = 127.73 MW
Electric power of the UCG power plant	P_{el} = 76.6 MW
Thermal power of the UCG power plant	P_{ther} = 44.7 MW
UCG thermal power produced	$Q_{heatUCG}$ = 33,371,446 GJ
UCG electric power produced	$W_{electricityUCG}$ = 57,208,192 GJ

The value of the available thermal energy of gas at the efficiency of 80% from one module is calculated to $W_{module80\%}$ = 9,192,960 GJ, which coincides with the estimated value of the available thermal energy of $W_{gas80\%}$ = 9,269,846 GJ in the laboratory, as the difference between both values is insignificant. Consequently, the same applies for power, as the value of the available thermal power is calculated to $P_{UCG80\%}$ = 126.66 MW, which coincides with the estimated available thermal power of $P_{gas80\%}$ = 127.73 MW obtained in laboratory. This demonstrates that the estimates concerning the size class of the technological parameters for the dimensioning of the UCG facility are correct.

The efficiency of the electrical transformation in the above-ground facility or thermal power plant fuelled by syngas obtained from UCG that we took into account was $\eta_{powerplant\text{-}el}$ = 60%, which, for the future, is a more and more acceptable value of the transformation of gas energy into electric energy. The estimated electric power of a potential thermal power plant for one module within the UCG facility, while taking into account the efficiency of the transformation of $\eta_{powerplant}$ = 60% and the gasification efficiency of $\eta_{gasification}$ = 80%, is thus P_{el} = 76.6 MW. The estimated thermal power of a potential thermal power plant for one module within the UCG facility, while taking into account the efficiency of the thermal transformation of $\eta_{powerplant\text{-}thermalpower}$ = 35% and the gasification efficiency of $\eta_{gasification}$ = 80% is $P_{thermalpower}$ = 44.7MW.

UCG economic analysis

The economic period of the UCG project is $t_{UCGproject}$ = 28 years (4 years of investment and 24 years of operation) during which the operation of ten modules is envisaged (28 months for one module). The economic period was assessed on the basis of the gasification scheme proposed by Carbon Energy [8,16]. It has to be noted, however, that the exact time of operation will be deduced from the actual rate of the cavity increase of the Velenje lignite. In the literature, a 2-year-long realisation period (building UCG installation and producing electricity) and a 20-year-long exploitation period assessments can be found [20,21].

The total costs of the UCG project are represented in Table 4. These are all the costs from the beginning to the end of the project, and cover the construction and operation of the underground UCG facility (ten modules) and the entire above-ground UCG facility. Total costs of the UCG project including the implementation of investment (4 years) and a 24-year operation with no depreciation taken into account are $S_{UCGcosts}$ = 466,158,070 €. Total costs of the UCG

project thus equal the sum of investment costs and operating costs. Total operating costs of the UCG project are: the manufacture and operation of modules, overheads, labour costs, financing costs in the total amount of $S_{\text{oper.costsUCG}}$ = 297,865,536 €, where a substantial part goes for the costs of manufacture and operation of modules S_{izdobr} = 248,422,379 €. The operation cost per year is therefore 10,638,055 €, which is comparable to the results of Nakaten et al. [20], who estimated these at 8,116,000 € per year.

Table 4. Total costs of UCG project

Cost type	Estimated cost, €
1. Investment costs	168,292,534
2. Operating costs	297,865,536
2.1. Manufacture and operation of modules	248,422,379
2.2. Overheads	9,600,000
2.3. Labour costs	16,254,956
2.4. Financing costs	23,588,201
Total costs	466,158,070
Different manners of coal exploitation	Estimate of revenues, €
Coal from 10 modules is sold to TEŠ (Thermal Power Plant Šoštanj)	287,280,000
Underground coal gasification	594,627,670
Underground coal gasification at 80% gasification efficiency	514,476,450

The more accurate value of investment or the estimated contract value of the Velenje UCG project is estimated to be $S_{\text{estimatedcontrvalue}}$ = 168,292,534 € and has been calculated on the basis of fixed prices *i.e.*, on the basis of the prices that are currently in force. It includes all the necessary investments, which are necessary for the initiation of regular production or operation of the UCG facility: costs related to the purchase of land, project dossier, implementation of research wells, electric and engineering equipment, surface infrastructure, the manufacture of the first module including the costs of drilling and piping and other costs and unforeseen works.

The technological UCG facility on the surface or the equipment of the thermal power plant fuelled by syngas obtained from coal is founded on the conceptual technological scheme of the facility shown in Figure 3 and on the data from Table 3.

As for the above-ground facility, the following elements generate the large part of costs: steam turbine, steam turbine generator, gas turbine, gas turbine generator, cleaning of syngas, combined cycle boiler, oxygen injection, CO_2 collector as well as special characteristics and requirements of the facility ensuing from the location of the future thermal power plant itself. The costs of the necessary infrastructure on the surface including the construction of roads, the establishment of links with electric power network and district heating network and reagent storage facilities, laboratory and management building, the installation for the production of chemicals and/or fuels or the entire thermal power plant for the production of electricity and thermal energy must not be forgoten.

A large part of the cost related to the underground facility is linked to the costs of drilling and installation of pipes or piping for the provision of reagents and for the extraction of the produced gas. Basically, the costs of the UCG process represent the costs of fuel and depend on the actual state of development of individual UCG methods.

By installing the UCG facility, the costs of preparing the reactor, *i.e.*, the drilling of the wells and the installation of the pipes represent the largest amount of costs. The price of the necessary equipment and of the work required is very high as the entire gasification process takes place underground. Thickness and depth of the coal deposit, the number of wells which need to be drilled, the multiple use of individual wells for the adjacent fields of coal – all of this plays an important role in estimating the costs. Consequently, the choice of the UCG method depends, to a large extent, on a minimization of costs related to drilling or to the length of wells, which need to be drilled, in order to reach the coal seam and to prepare the field to be gasified.

The costs of drilling and pipe instalation along the wells are highly variable, especially if we also take into account the costs of research wells and wells used for monitoring and control.

Since the sources of financing for the entire UCG project in Velenje are not yet known, the financing method was estimated. The following financial construction of investments is envisaged: 50% will be financed from own resources and 50% from a long-term bank loan.

The costs of the necessary installations for the underground coal gasification are estimated to be lower than the costs of the installations required for conventional mining at the same capacity. With the UCG method, there are also no costs of mining and coal transport compared to conventional procedures for producing electricity and thermal energy. It is also estimated, that the price of the electric and thermal energy obtained with the UCG method is lower than the price of energy obtained from conventional thermal power plants. However, the syngas obtained through the process of underground coal gasification

cannot compete, in terms of price, against a conventionally obtained natural gas.

The choice of the reagent used (air, air enriched with oxygen, oxygen and/or addition of steam) has a huge impact on the economy of the process. This to a large extent defines the composition and calorific value of the obtained syngas, which can then be used in many different ways. The costs related to the reagent itself will be much higher if an air separation unit is needed which ensures a sufficient amount of oxygen.

The economy of the UCG process mostly depends on the geological properties of coal and on the use of land on the surface above the reactor cavity. From the economic point of view it is better to own a coal deposit where the project of underground coal gasification can be carried out. The depth itself and other geological and hydrological properties will have a direct impact on the costs of drilling and on the implementation of the underground link between the wells.

Table 4 contains the estimates of revenues for different cases of coal exploitation for the selling of thermal energy. In estimating the revenue, if the coal was sold to Thermal Power Plant Šoštanj, the revenue is estimated to be $P_{\text{revenues10modulesTE}}$ = = 287,280,000 €. A selling energy value of coal of c_{coalTE} = 2.5 €/GJ and calorific value of the Velenje lignite of h_{lignite} = 10 GJ/t have been taken into account in our estimation. An estimate of the revenue in the event of underground coal gasification at both 100% and 80% efficiency of energy transformation was also made. In case all thermal energy, obtained from the underground part of UCG of all ten modules was sold on the market, the estimated revenue would be $P_{\text{revenue10modules}}$ = 594,627,670 €. Taking into account the efficiency of gasification of 80% the estimated revenue from sales of all produced thermal energy from the underground UCG facility of all ten modules would be $P_{\text{revenue10modules80\%}}$ = 514,476,450 €.

Continuing the calculations, if it is assumed that all the produced thermal and electric energy obtained from UCG at 80% gasification efficiency will be sold on the market; the use of energy needed for the operation of the UCG facility was considered and calculated as a cost. The fact that the facility operated continuously with constant production of thermal and electric energy every year was also taken into account. Once the operation of one module concludes, the operation of the next module continues.

The total anticipated revenue from sales of thermal energy obtained through the UCG process for the duration of the project is estimated to be $P_{\text{revenueheatUCG}}$ = 185,211,523 €. Total anticipated revenue from sales of electric energy of UCG for the duration of the project is estimated to be $P_{\text{revenueelectricityUCG}}$ = 953,660,568 €. Total anticipated revenue from sales of thermal and electric energy on the market at 80% gasification efficiency for the entire duration of the UCG project is $P_{\text{revenueUCG}}$ = 1,138,872,091 €. In our calculations of revenues from sales of thermal and electric energy the selling price with regard to the average selling price for 2009-2018 period in the HSE Group, namely the thermal energy price c_{heat} = 5.55 €/GJ = 20 €/MWh and the electric energy price $c_{\text{electricity}}$ = 16.67 €/GJ = = 60 €/MWh were taken into account.

The UCG's performance per individual year with the review of revenues and expenditures with a default gasification efficiency of 80% are shown in Figure 4. During the entire operating period of UCG, the entire project will have revenues in the amount of

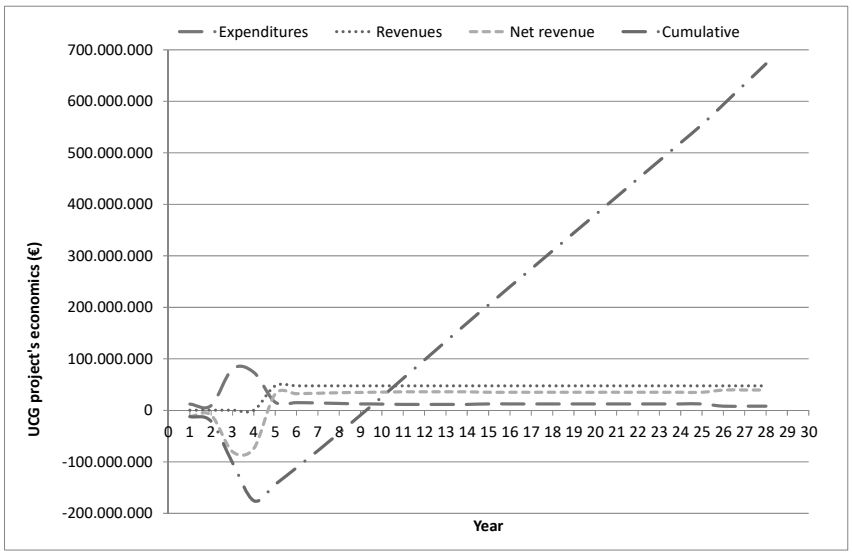

Figure 4. Financial flow of the entire UCG project.

$P_{revenueUCG}$ = 1,138,872,091 € and expenditures in the amount of $S_{costsUCG}$ = 446,374,865 €. Total profit and loss or profit for the entire project for the entire duration of the operation of UCG is $D_{profitUCG}$ = = 692,497,231 €; however the cost of concession for the exploitation of coal and costs related to potential unforeseen incidents have to be taken into account. In calculating profit and cumulative of UCG performance, the remaining part of investment $S_{remainvalue}$ = = 19,783,210 €, which represents the difference between the investments made and depreciation, and defines the accounting value at the end of the UCG project, was taken into account.

The basis for the calculation of the financial performance of the UCG project is the financial flow of the project. The financial flow comprises a 4-year investment period and a 24-year operation period (economic period of the project). The basis for the calculation of the performance criteria is the financial flow of the investment and not the entire cash flow. The financial flow revenues are comprised of revenues from sales of thermal and electric energy and the remaining part of the project's value in the amount of non-depreciated value of fixed assets in the amount of $S_{remainvalue}$ = 19,783,210 €. The expenditures of financial flow are comprised of the value of investment (without financing costs) and operating costs (without depreciation). The financial flow of the entire UCG project is shown in Figure 4.

Statistical and financial indicators concerning the viability of the investment show that the investment is repaid after the operation of the third module, which is also shown in Figure 4. Here, a modular system of ten modules, where the envisaged operating period of one module extends over 28 months, was taken into account.

The basis for the estimate of the viability of the UCG investment is the financial flow. A discount rate of d = 7% is used. The present value of the covered project means, that when it is calculated according to the present money value, the investment would – after the costs of the entire investment have been covered – create further $P_{netpresentvalue}$ = 139.130.209 € of accumulation at the end of the project's period.

The intern rate of profitability is $f_{internrateprof}$ = = 16.08% and refers to the average annual rate of profitability of the investment during the life cycle of the project which is $t_{projectUCG}$ = 28 years.

Relative net present value of investment is $f_{relativenetpresvalue}$ = 0.901 and means that until the end of its economic period the investment will "gather" investment funds in the amount which will, at that given time, enable the investment of 90.1% share of an investment project of the same scale.

The period of repaying the costs of investment refers to the time required for the investment revenues to cover the entire amount of investment expenditures. In our case, the investment is repaid in year 10 of the economic period of the project.

The very different conditions in which individual tests took place must mean that any generalisation of the results is not acceptable and could even be dangerous; therefore, the results of each test can only be treated as specific to its own conditions. All the tests were small scale ones, and not one resulted in a commercially acceptable technology that would meet all environmental requirements. The site-specific techno-economic analyses have to be undertaken for each selected underground coal gasification study area individually, whereas results cannot be transferred from one target area to another [20]. The technical feasibility and economic success of a UCG project is highly site-specific [22].

Based on a life cycle costing analysis, Burchart-Korol *et al.* [21] concluded, that for cost effective production of electricity with UCG it is necessary to maximize the scale of an installation while optimizing the use of the produced electricity. The implementation of carbon capture and storage CCS causes an efficiency reduction of only 5-8% [20]. The costs consist of CO_2 separation, transportation, compression and injection, storage and monitoring costs. There are no transportation costs, since CO_2 is to be stored in the voids.

A techno-economic model for UCG was developed by Nakaten *et al.* [20], which combined UCG with a combined cycle gas turbine (CCGT) considering CO_2 capture and its subsequent storage (CCS) in the underground voids for a study area in Bulgaria. Their calculation results show that COE account to 48.56 €/MWh without CCS or emission charges, to 71.67 €/MWh considering 20.5% CCS costs and 79.5% emission charges and to 73.64 €/MWh with 100% emission charges [20]. The calculations in this work show that the cost of electricity can be as low as 20 €/MWh, which is the same value as is presented in the work by Pei *et al.* [22]. It has to be, however, considered that energy loss in a UCG process typically occurs due to water influx, underground cavity pressure drop, gas loss to the surrounding strata, and high temperature gasifying medium, which raises the cost of operation and lowers the product gas quality and profit [23]. It should also be considered that adaptations during the course of operation will be performed and that the syngas quality will vary from time to time.

Underground coal gasification has been gaining interest for the production of syngas due to the favourable economic outlook, for the use of coal in areas which are not suitable for conventional mining, for the production of electric and thermal energy and as a method of producing clean fuels. On the basis of comparison between the processes of gasification of different types of coal, and on the basis of understanding the strategies of management of individual processes, some companies have already developed key parameters for the planning or commercialisation of the UCG process.

The evolutions in the field of UCG show that the process is potentially very interesting, as preliminary research and studies about the possibilities of UCG have been performed in numerous countries. The UCG process is listed among potential possibilities for solving energy issues in the near future, as it is mentioned in long-term national development plans for exploiting natural resources.

This paper contains the presentation of the implementation of energy and economic analysis of the operation of one module and modular plant for a hypothetical case of gasification of the Velenje lignite according to the CEPL method. A new calculation procedure is also presented, which was, in the framework of energy and economic analysis, used to justify the use of lignite according to the used method. The conventional mining method, the ideal process of underground gasification and a default realistic efficiency of the underground gasification were compared. It was concluded, on the basis of energy and economic analysis, that the UCG project for the Velenje lignite at the location of Tičnica is feasible. This energy analysis presents real possibilities of exploiting the remaining lignite reserves in the Šaleška valley and also indicates the opportunity to exploit brown coal reserves in north-eastern Slovenia. Since very few UCG tests were made in the world, this represents an important energy, environmental, and business opportunity both in Slovenia and abroad.

CONCLUSION

The crucial decision concerning the UCG project, which also serves as the basis for the technical and economic viability of the project, is the choice of the appropriate location and its characterisation. The adequacy of individual fields of coal for the UCG method depends on many factors including physical and chemical characteristics of the coal itself, geological and hydrological properties of the field, environmental, energy and economic adequacy. There were very few tests performed around the globe on lignite and not one was performed on the thicker layers comparable to the one in Velenje, where the development of the combustion cavity differs from the one in thinner layers. The Velenje coal seam is one of the thickest individual coal seams or one of the thickest uniform layers of, especially lignite, in the world. Since the Velenje coal field is unique, there are no comparable studies available in the literature. Consequently, research is very important and at the same time also very difficult to perform. Based on the existing UCG method, a unique energy-economic analysis was executed, which has not been done so far. This energy-economic analysis is the only one in the world that applies to the exploitation of lignite at shallow depths and in the operating coal mine at the same time.

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NAUČNI RAD

PODZEMNA GASIFIKACIJA UGLJA - ENERGETSKI I EKONOMSKI PRORAČUNI ZA RUDNIK UGLJA VELENJE

Podzemna gasifikacija uglja (PGU) je održiva mogućnost za eksploataciju ogromnih ležišta uglja koji su nedostupni konvencionalnom rudarstvu i može da zadovolji energetske, ekonomske i ekološke zahteve 21. veka. Zbog složenosti procesa, specifičnosti nalazišta i svojstva slojeva uglja, veoma je važno da se poznaju svi raspoloživi podaci i iskustva iz prošlosti, radi uspešnog obavljanja PGU operacije. Slovenija ima ogromne neiskopane rezerve uglja, i zato nudi mogućnost alternativnog korišćenja ovog domaćeg primarnog izvora energije. Prema dostupnoj tehnologiji za podzemnu gasifikaciju uglja, napravljena je energetska i ekonomska procena eksploatacije uglja za generisanje električne energije i toplote. Predložen je novi postupak za procenu energetske efikasnosti procesa gasifikacije uglja, koji je korišćen za uporednu analizu različitih primera eksploatacije uglja , kao i tehnološke šeme i način rada postrojenja u Velenju za proizvodnju sinteznog ugljenog gasa (singas). Pregledana je predložena lokacija za pilot demonstracioni eksperiment u rudniku uglja Velenje i utvrđena je održivost projekta PGU u Velenju.

Ključne reči: podzemna gasifikacija uglja, singas, čiste tehnologije za ugalj, energetska analiza, ekonomska analiza.